Method for self-supported transfer of a fine layer by pulsation after implantation or co-implantation

Field of the invention

The invention relates to a method of transferring an ultrafine film (the term thin or ultrathin film is also used) using self-supported propagation of a fracture initiated by a pulse of energy. It has applications in particular in the fields of micro-electronics, micro-mechanics, optics and integrated electronics.

State of the art

As is known, splitting a thin film may be achieved by implantation of chemical species in a source substrate, for example of silica, to induce the formation of a zone of defects at a particular depth. These defects may be micro-bubbles and/or platelets and/or micro-cavities and/or dislocation loops and/or other crystalline defects, locally disrupting the crystalline quality of the material; their nature, density and size are strongly dependent on the species implanted (typically hydrogen) as well as on the nature of the source substrate. A heat-treatment may then be applied to enable the development of specific defects present in the weakened zone, which enables splitting of the thin film from the source substrate to be achieved later. This has

in particular been described in the document US-5 374 564 and developments thereof, such as the document US-6 020 252.

However, spontaneous splitting during thermal annealing is sometimes ill-suited to certain situations, for example when the substrates brought into contact have different coefficients of thermal expansion. Moreover, it is known in the art (see for example US - 2003/0134489) that, in the case of a fracture obtained by thermal means, and under certain conditions, the latter preferentially commences at a localized place on the wafer, which can sometimes lead to surface non-homogeneities that are reflected in the form of a "marbled" type appearance. These irregularities also appear in the case of a purely thermal facture when attempting to overfragilize by implanting an overdose of a species such as hydrogen in such a manner as to facilitate the fracture thereof or to minimize the thermal budget (temperature-duration) subsequently applied to the wafers.

When the splitting is produced at high temperature (typically near approximately 500°C), among the technological problems sometimes encountered, mention should be made of the roughness of the surface as well as the degradation of the film transferred during the thermal splitting. This renders the following treatment steps more difficult (for example: the transferred film must be polished more, there is a risk of crystalline defects being created during the following treatments, etc.). Furthermore, in heterostructures (comprising a superposition of substrates of different materials), another technological problem encountered is the presence of a field of very high stresses in the various films in contact, during the heat treatment, due to the difference in the coefficients of thermal expansivity of the various

materials placed in contact. This may induce the degradation of the heterostructures if the thermal splitting occurs at a temperature higher than a critical temperature. This degradation may, typically, be the breakage of one or both substrates brought into contact and/or be the unbonding of the substrates at the bonding interface.

This is the reason why it may be desired to achieve the splitting at lower temperature.

One way to achieve splitting at low temperature is to "play" with the implantation conditions. For example, an excess dose of the implanted species may increase the weakening of the implanted zone and cause splitting at low temperature by providing an external force.

Splitting may also be effected by applying an external force that causes the fracture in the weakened area until the thin layer is detached, generally after heat treatment. See in particular the document US - 6 225 192 (CEA).

It is important to note that, for a given substrate and given implantation conditions, it is not only the treatment temperature that conditions the subsequent conditions of splitting of the thin layer, but also the duration of that treatment, which is reflected in the thermal budget concept (see FR-2 767 416 - CEA); as for the provision of mechanical energy, it is applied for example by a "guillotine" type tool (see WO 02/083387 - SOITEC).

Thus Henttinen et al. (2000) [1] showed that, if the source substrate is a wafer of silicon, a dose of hydrogen ions implanted at 1×10^{17} H^+/cm^2 (i.e. 5×10^{16} H_2/cm^2), enables splitting by a mechanical force after performing the following steps: treatment, as for the target substrate, by a plasma chemical activation;

cleaning of RCA1 type, bonding at ambient temperature of the source substrate onto the target substrate, and annealing at 200°C for 2 hours. The mechanical force utilized came from a blade inserted at the bonded interface to initiate the splitting.

This approach, although reducing the roughness of the transferred surface (by of the order of half with respect to conventional splitting solutions that are purely thermal and without plasma activation), involves slow and jerky propagation of the fracture wave. Thus Henttinen reports that each forward movement of the blade leads to the propagation of a fracture that is stabilized over a certain distance after two minutes.

This type of mechanical splitting therefore consists of introducing a blade from the edges of the structure and moving this blade forward over virtually all of the bonded structure, as if to "cut it out" along the weakened zone; the term 'assisted splitting' is sometimes used, since the role of the tool (such as a blade) is to propagate the fracture wave from one edge of the structure to the other.

This type of fracture leads to the following defects, at the future surface freed by the splitting of the thin film:

- crown defect (non-transferred zone, at the periphery of the final product), for example related to a local bonding energy too low with respect to the rest of the interface, and to the introduction of tools to start off the transfer,
- lack of uniformity (low frequency roughness) of the thickness of the thin film transferred, in particular due to the fracture wave assisted mechanically, thus irregular, by fits and starts, which then necessitates treatments,

such as polishing, which it is however generally sought to avoid,

- difficult industrial implementation, given the use of a tool which accompanies the propagation of the fracture, which implies an individual treatment of each structure (or wafer).

Moreover, it has been found that, if the thermal budget is too low, the transfer of the thin film is of poor quality, whereas if it is too high, fracture of one of the substrates may occur in the case of a heterostructure. It is therefore clear that in theory there is a narrow window for the operating parameters (of course linked to the conditions, in particular the doses implanted, the nature of materials, the annealing temperatures, etc.); now, this narrowness constitutes a heavy constraint for industrial exploitation.

Most of these drawbacks are found in the case of the splitting of a thin film in a homogeneous substrate (with a single component material (SOI, for example).

The splitting of the thin film is of course also determined by the choice of the chemical species implanted.

It was indicated above that hydrogen is generally implanted, but other options have been proposed, in particular by implanting helium.

Combination may even be made of two different chemical species.

Thus Agarwal et al. (1998) [2] found that the fact of implanting both hydrogen and helium enabled the total implanted dose of ions to be reduced, apparently due to the different roles played by hydrogen and helium: the hydrogen interacts with the Si-Si bonds broken by the implantation, to create Si-H bonds, resulting in a high density of platelet type defects of a size of the order of 3-10 nm (termed H-defects of platelet type), whereas

helium, which does not act chemically, leads to the appearance of a lower density of larger defects (size greater than 300 nm approximately). The heat treatments envisaged in that article are 450°C for 20 min or 750°C for 20s, which necessarily implies the drawbacks mentioned above in relation to splitting at high temperature.

This hydrogen-helium combination has also been studied, in a more theoretical manner, by Cerofolini et al. (2000) [3], who noted that pressurization of the defects was greater with the implantation of helium than with that of hydrogen, and that the heat treatment could have different effects according to the temperature chosen: annealing between 150°C-250°C leads to a reduction in the number of Si-H bonds, annealing in the range 300°C-450°C leads on the contrary to an increase in that number, whereas annealing above 550°C tends instead to reduce that number again. However that article does not deduce practical conclusions therefrom as to the manner of obtaining thin films of good quality (in particular in relation to the state of the surface) for a moderate cost.

An object of the invention is to alleviate the drawbacks described above.

More particularly, the invention relates to a method of transferring a thin film that can be carried out at low temperature (in order to limit the high mechanical stresses when using materials having large coefficient of expansion differences), that can be effected collectively and limiting the defects cited above during splitting of the thin layer, in particular by preventing jerking of the fracture wave. In other words, an object of the invention is to obtain, for a moderate cost, thin films of high quality, thereby avoiding at the same time the drawbacks of a heat

treatment at high temperature and those related to the utilization of a tool for assisted splitting, and those related to an additional treatment for reducing roughness after splitting.

Presentation of the invention

To that end the invention provides a method of self-supported transfer of a thin film according to which:

- a source substrate is prepared,
- at least a first species of ions or gas in a first dose at a given depth is implanted in that source substrate with respect to a face of that source substrate, that first species being adapted to generate defects,
- a stiffener is applied in intimate contact with the source substrate,
- a heat treatment is applied to that source substrate, at a given temperature for a given time, so as to create, substantially at the given depth, a buried weakened zone, without initiating the thermal splitting of the thin film,
- a pulse of energy is applied to that source substrate so as to provoke the self-supported splitting of a thin film delimited between the face and the buried weakened layer, with respect to the remainder of the source substrate.

Self-supported splitting may be defined here as being a complete and virtually instantaneous splitting, similar to that obtained by a simple heat treatment at high temperature, but possibly induced by a tool without it having to follow any kind of fracture wave (if there is a tool, it comes at most into contact with the substrate and the film, without following the splitting interface); this is thus, in other words, the contrary of an assisted splitting. It may also be referred to as a

"self-supported" phenomenon.

Two species, for example hydrogen and helium, may preferably be co-implanted, as described in the application FR2847075 or the application WO-04/044976; the implantation of a plurality of species can be concomitant or not.

The heat treatment temperature is advantageously chosen to promote the development of crystalline defects in the weakened area without in so doing leading to spontaneous thermal splitting. This temperature will be sufficiently low not to generate mechanical stresses that are too high in the substrate assuming that the source substrate and/or any target substrate include materials having very different coefficients of expansion. This is why the method is a transfer method occurring at a relatively low temperature (not greater than 500°C in the case of a silicon/quartz heterostructure, for example).

According to the invention, the fracture is obtained by propagation of a self-supported fracture wave, after the latter has been initiated by an energy pulse applied in a fragile area (this pulse being local or global). To obtain this phenomenon, implantation conditions (dose, energy, nature of the species, current, order of implantations (if there is more than one) and relative positions in the depth of the substrate of the implanted species (in the case of implanting a plurality of species), implantation temperature, etc.) and appropriate treatment (for example heat treatment) would seem to enable shaping of the distribution, the morphology, the size of the crystalline defects (cavities, platelets, microbubbles and macrobubbles and other types of defects) that form the fragile area. It is precisely the work of shaping the fragile area that seems to enable the result of self-supported fracture to be obtained.

The invention consists in promoting weakening conditions close, in their nature, to the conditions obtained in the event of thermal fracture, without going so far. The additional energy is then provided by impulsional addition of energy at the end of or during the heat treatment, and induces the propagation of a self-supported fracture.

Self-supported propagation of the fracture wave means that it is not necessary to assist the propagation of the wave by advancing a tool or repeating the initiation energy pulse. Also, an important feature of the invention is that the fracture wave is propagated over the whole of the surface of the wave in less than 1 second, or even of the order of one millisecond (speeds greater than 100 m/s) for diameters up to 300 mm.

One possible origin of the self-supported (or self-supported) fracture stems from the nature of the buried defects. Research (on germanium, but applicable to silicon) has shown that under self-supported fracture conditions the density of defects (microcracks, cavities, platelets, microbubbles, macrobubbles, etc.) is estimated to be from 0.03 to 0.035 per square micron, their sizes are of the order of 7 to 8 square microns, and the area opened up by these defects, as a percentage of the total area of the wafer, is estimated to be from 25 to 32%. These values characteristic of the weakened area might seem similar to characteristic values noted if the fracture is obtained by thermal means, but different from those obtained after weakening treatment that necessitates assisted mechanical fracture (in which case, the percentage of the area opened up is more of the order of 10%).

At least the condition cited above as to the area opened up is preferably applied (it seems to be the most important; it seems that it may be generalized to a range

from 20% to 35%), where appropriate complemented by either or both of the conditions as to the density or the size of the defects.

Of course other effects or causes are not excluded by this interpretation, and in particular the chemical nature of the bonds in the substrate may also promote the occurrence of the phenomenon of self-supported fracture wave.

In other words, the invention seems to consist in promoting weakening conditions close, in their nature, to the conditions obtained in the case of thermal fracture, without going so far. The additional energy is then provided by impulsional addition of energy.

It must be emphasized that it was not obvious for the person skilled in the art to arrive at such conditions enabling a self-supported fracture to be obtained, even if that result might seem in itself to be extremely desirable.

The person skilled in the art, seeking to improve the results of mechanical fracture, might have been incited to fragilize the substrate more, for example by increasing the thermal budget input to the implanted structure bonded to the stiffener substrate. And the person skilled in the art would have been able to verify that, by increasing the thermal budget, the force necessary to propagate the bonding wave was indeed reduced. However, he would not have been able to observe the self-propagated fracture wave phenomenon, which is produced only under particularly favorable conditions (see below). In particular, the person skilled in the art would not have thought to continue weakening as far as an ideal point that precedes the moment of thermal fracture, as under general conditions of implantation and of heat treatment, that point is an unstable point that it would be hazardous or futile to seek to achieve. In particular

in the case of fabrication of heterostructures, passing this unstable point, and therefore the thermal fracture of the substrate, often leads to complete breaking of the final product linked to the sudden releasing, at the time of the fracture, of the stresses of thermomechanical origin stored in the bonded substrates.

Accordingly, and at most, the person skilled in the art would have expected that the continuous force necessary to propagate the fracture wave would be less. Thus in particular he would have had no objective reason to think that simply prolonging the weakening annealing (over the prior art) followed by the application of an impulsional force would lead to a self-supported fracture wave.

In fact, the impulsional energy application may be global (thermal shock, ultrasound, etc.) or localized (laser, mechanical shock, traction force, etc.).

This pulse is preferably localized, and advantageously applied by a tool moved briefly with a small amplitude. This addition of energy is advantageously applied in the immediate proximity of the buried layer, limited to only a portion thereof, preferably to a peripheral portion thereof.

This pulse may also in particular consist of a localized thermal provision (for example applied by a laser pulse) or an external stress (for example in the immediate vicinity of the weakened area, at an edge thereof).

For reasons of simplicity of implementation, the fracture may be obtained at around room temperature (0 to 50°C), for example by application of a mechanical shock localized to the border of the assembly. However, this particular embodiment is not limiting on the invention, and in certain situations it may be preferable to initiate the fracture at a higher temperature, for

example around 300°C.

It has been observed that the energy pulse has had all its effectiveness for initiating the fracture wave when the latter led to a very localized opening up of the interface at the level of the fragile layer. Thus a shock provided by a blade type tool, or more generally any traction type force, induces the propagation of a self-supported fracture very effectively.

If the complementary treatment is carried out in the form of the application of a thermal budget, the latter is less than the thermal budget necessary to obtain the fracture.

The surface state of the substrate formed after fracture has high-frequency and low-frequency roughnesses improved over the prior art. This result is particularly pronounced for the low frequencies, in particular with the absence of fracture waves. It is assumed that this result is linked to the fact that, in the context of the invention, the fracture wave propagates continuously, without jerks and within a highly weakened layer (which would facilitate the propagation of the wave in a preferential area within the weakened layer), compared to what is obtained in the prior art.

Under standard implantation conditions (implantation of H^+ of the order of $5 \times 10\ 10^{16}$ at/cm^2 from 20 to 300 keV in silicon - Si) the self-supported fracture phenomenon is observed only for narrow operating points, which it may be difficult to reproduce systematically.

On the other hand, under different conditions, in particular, the operating window to obtain the self-supported fracture phenomenon is wide, which means that this phenomenon is observable for a wide variation of the parameters for obtaining the fragile layer (parameters of implantation and of the additional heat treatments, in

particular). This is the case, for example, when the implantation is a co-implantation under defined conditions (see below) and/or when the temperature profile of the additional treatment includes adapted phases. In the context of industrial use, it is important to make the method rugged vis à vis drift, inaccuracies and variations of the operating parameters which are inevitable, of course. In practice, this great ruggedness authorizes the use of the method for batches of wafers, rather than wafer by wafer, as is standard practice in the microelectronics industry. Thus it has been possible to verify that it was possible to obtain the fracture over a batch of wafers (25 wafers) using a wafer manipulation tool like that disclosed in WO03013815. It was also noted that the time necessary to implement the method corresponds substantially to the time to implement the prior art methods.

In other words, according to one particular aspect of the invention, the latter proposes a method of fabricating a batch of substrates including the following steps:

- implantation of each of the substrates,
- weakening treatment of the substrates as a batch,
- application of energy pulses simultaneously to each of the substrates (collective treatment).

It seems that it should be noted that, according to the invention, the substrate is weakened and the weakening "energy" does not need to be maintained up to the moment of application of the energy pulse. It may even be added that provoking self-supported propagation at high temperature is not recommended in the case of heterostructures, as the stresses arising from coefficient of thermal expansion differences, that are released at the moment of fracture, could lead to

breaking of the substrates.

It is worth stressing that, according to the invention, under certain conditions of implantation, the implanted area is weakened very strongly without generating purely thermal splitting, and this even for very high annealing temperatures (no splitting observed after 24 h of annealing at low temperature as defined below); on the other hand, self-supported splitting is initiated by simple addition of impulsional energy (such as a mechanical shock at the level of the weakened interface, for example).

The consequences of this are significant:

- the operating window of the annealing step may be very wide: the maximum limit for the duration of this pre-weakening annealing is pushed back a long way (or even no longer exists); this is entirely favorable to the industrialization of the process,
- there is no assisted splitting since the self-supported fracture enables the fracture wave to propagate instantaneously and without jerks over the whole of the area of the wafer; it is not necessary for any blade to penetrate between the substrate and the future thin film, which avoids damaging the layer transferred by the splitting tool. The self-supported fracture also clearly improves the topology of the surfaces exposed in this way (for example with lower roughness (especially at low frequency)), and avoids crown defects, which renders the whole of the thin film usable, including its periphery,
- the fact that it is no longer necessary to introduce any tool is also favorable to the industrialization of the process and to collective treatment of the substrates by batches of wafers.

In that, at the latest at the time of the heat treatment, the source substrate is placed in intimate contact via said face with a stiffener or target

substrate, the heat treatment contributes to improving the energy of bonding between these substrates.

This target substrate or stiffener is advantageously chosen from monocrystalline or polycrystalline materials, such as silicon or sapphire in particular, or in the form of an amorphous material, like for example in the form of fused silica.

According to one particularly advantageous feature of the invention, a plurality of species are implanted concomitantly or otherwise. This may advantageously be co-implantation of hydrogen and helium.

Advantageously, in the case of helium, in the case of hydrogen-helium co-implantation, hydrogen may be implanted (preferably in H^+ form) with a relatively low dose (typically of the order of a few 10^{16} H/cm^2), bearing in mind that hydrogen exhibits a high efficacy for creating a weakening layer. At the level of that layer, helium may be implanted at a relatively low dose (typically of the order of 10^{16} He/cm^2, or a few 10^{16} He/cm^2).

When the source substrate has been bonded to a target substrate, the low-temperature heat treatment (the temperature is nevertheless sufficient to obtain good solidity of the bonding interfaces) has the effect of allowing the splitting of an ultra-fine and very smooth film (roughness of the order of a few nm), initiated by an exterior pulse. The advantage of co-implantation is obtaining maximum weakening of this area at the temperature sufficient for the solidity of the bonding interfaces without this meaning having to reach excessive temperatures that heterostructures would not be able to withstand and without either being obliged to use very high implantation doses (which is a known means of limiting the value of the temperature necessary to develop the weakened area).

The two species are advantageously implanted at the same level but one variant consists in offsetting the implantation profiles. The two species may be implanted in any order, but it is advantageous, in the case of a silicon substrate and hydrogen-helium co-implantation, it is preferable to implant the deeper profile first.

In fact, at least when proceeding to a hydrogen-helium co-implantation in a silicon substrate, a heat treatment temperature from 200°C to 400°C may be chosen.

The source substrate is preferably of a material chosen from semiconductors and insulators, monocrystalline, polycrystalline or amorphous. Thus it may be chosen from the IV semiconductors; a particularly beneficial example is silicon but it may also be germanium or Si-Ge alloys. It may also be materials from the III-iV family or II-Vi materials such As-Ga or InP, or in insulative material such as ferro-electric materials, for example LiNbO3 and LiTaO3.

The heat treatment may also have a profile adapted to reduce the time of that treatment, as is for example disclosed in European patent application No. 02-293049 filed on December 10, 2002.

In fact, the temperature range depends principally on the nature of the species implanted and on the nature of the material constituting the source substrate, and on the nature of the stiffening substrate, especially in the case of a heterostructure.

General description

Aims, features and advantages of the invention will appear from the following description, given by way of non-limiting illustration with reference to the accompanying drawing in which:

- Figure 1 is a diagram of a source substrate during implantation,

- Figure 2 is a later view of it after putting in intimate contact (bonding) with a target substrate; and
- Figure 3 is a view of it during splitting of a thin film deriving from the source substrate.

Figure 1 thus shows a substrate 1, for example of silicon advantageously oxidized on its surface 4, while being subjected to an implantation treatment, represented by the arrows 2, for example by bombardment with ions or gaseous species.

This implantation involves, at a given depth, implantation of a first species which is adapted to generate defects, for example hydrogen, preferably in the form of H^+ ions. In a preferred embodiment of the invention, this implantation may be a co-implantation of two species, for example hydrogen - helium. In the case represented, the two species are implanted to the same depth, but alternatively it is preferable for the first species implanted to be that whose profile is deeper, for example the helium before the hydrogen.

Specifically a start is made by implanting the first species, i.e. hydrogen, further to which the helium may be implanted. However, the inverse order of the implantations may be preferable, even if the two implantations are not made at the same depth.

A buried zone 3 results from this, weakened by the presence of defects.

The weakened zone 3 delimits, within the source substrate, a future thin film 5 and a substrate remainder 6, that is to say that which remains of the source substrate after splitting of the thin film; this remainder will be able to serve as source substrate for a new implementation cycle of the procedure.

Figure 2 represents a step during the course of which the source substrate, containing the buried

weakened zone 3, is placed by its face 4, into intimate contact with a corresponding face of a target substrate 7, typically by direct molecular bonding, whose function is that of a stiffener.

A heat treatment is then applied which will, on the one hand, enable development of the weakening of the buried layer 3, and on the other hand, when a bonding step has taken place, enable consolidation of the bonds between source substrate and target substrate.

More particularly, the temperature of this heat treatment is chosen from the range of temperatures suitable for developing the weakened zone.

This treatment is advantageously carried out at a temperature chosen from the range 200°C-400°C, preferably from the range 300°C-350°C, for a duration typically chosen of a few hours, for example 2 hours. Thus, the thermal budgets (temperature-duration pairs) are industrially realistic.

In Figure 3 there is represented the step of splitting of the thin film 3 from the remainder of the source substrate, by means of the application of an impulsional provision of energy, preferably brief and of limited amplitude, for example in the form of a shock or pulse.

It is for example constituted by a mechanical stress represented by the arrow 10.

The splitting obtained is self-supported in the sense that, in particular, there is no movement of a tool along the weakened layer.

This local provision of energy is here limited to a part of the buried layer, represented in the form of a corner effect corresponding to a shock applied by a tool such as a blade on (or proximal to) a portion of that buried weakened layer; but it may be of any other nature, for example a couple parallel to the plane of the buried

weakened layer advantageously applied in the form of a pulse of small angular amplitude. By virtue of the method of the invention, the face of the thin film which is freed by the self-supported splitting in the buried weakened zone (in practice substantially planar) has a roughness Ra considerably less than with the conventional solutions, without it having been necessary to provide a particular treatment of the surfaces transferred nor substantial ("coarse") polishing after splitting. It is worth noting that, since splitting is self-supported, there is no real propagation in fits and starts of a fracture wave liable to generate surface waves, and that, since there is no movement of any tool along newly created surfaces (or relative movement between the two parts on each side of the buried layer) there is no degradation of the surfaces thus freed, which therefore have a very smooth surface state, induced by the self-supported splitting.

The source substrate 1 may not only be of silicon, but more generally of any appropriate known material for example a IV, III-V or II-Vi semiconductor, ferroelectric, monocrystalline or polycrystalline or even amorphous. Thus the source substrate may be:

- another semiconductor of column IV of the periodic table of the elements, for example of germanium,
- a semiconductor of type III-V or II-VI such as AsGa or InP, in particular,
- an insulator, for example of niobate or tantalate type, such as $LiNbO_3$ or $LiTaO_3$, in particular.

The target substrate may be of a wide variety of materials, to be chosen according to needs, monocrystalline or polycrystalline (for example semiconductors, for example from among the same materials

as for the source substrate) or even be amorphous (for example types of glass, or polymers); thus it may in particular be:

- a crystalline material such as sapphire,
- of fused silica or of another glass,
- a simple stiffening layer, for example of oxide a few microns thick, deposited by any appropriate known technique (this admittedly no longer corresponds to a bulk target substrate of the type represented in the drawings).

It is worth noting that the target substrate may be just an intermediate substrate from which the thin film is later transferred onto a final substrate.

Examples

Co-implantation

According to a first embodiment of the invention, a substrate of Si (~700μm) comprising a layer of thermal SiO_2 on the surface (for example 145nm) may be implanted initially with helium atoms under implantation conditions of 70keV-1 $\times$ 10^{16} He/cm², and then be implanted with hydrogen atoms under implantation conditions of 30keV-4.25 $\times$ 10^{16} H/cm². The deeper profile for the implantation is thus performed first. This source substrate may next be joined to a target substrate of Si (~700μm) by molecular bonding. A heat treatment around 350°C for a certain time (for example 2 h) is then applied to the structure. If the heat treatment is suitable, for example as disclosed in the European patent application 02-293049, the window for obtaining the self-supported fracture phenomenon is of the order of a few hours (i.e. a weakening annealing from 2 to 6 hours). Then, with scarcely the commencement of insertion of a blade between the bonding interfaces in the form of a shock, self-supported splitting at the location of maximum hydrogen

concentration leads to the transfer of the thin film of Si onto the target substrate. Thus these trials with co-implantation of hydrogen and helium in the source substrate under the conditions of the invention led to a self-supported splitting, i.e. a complete and quasi-instantaneous splitting, with a continuous and plane propagation of the fracture wave, self-supported, initiated with the aid of an impulsional energy addition, which had in particular the advantage of avoiding surface undulations, i.e. of avoiding important variations of surface roughness after fracture, compared to progressive detachment. Because of this, this impulsional splitting implies thereafter less polishing.

The roughness of the surface transferred measured at high frequency (by atomic force microscopy), of the order of 45 to 50 angstroms RMS, and at low frequency (by profilometric method), of the order of 10 angstroms RMS, of that transferred surface are substantially less than those which may be obtained in the case of H-implanted alone ($32keV-5.5x10^{16}H/cm^2$) followed by a heat treatment at 500°C (roughness at high frequency of the order of 75 angstroms RMS and roughness at low frequency of the order of 26 angstroms RMS).

According to another embodiment of the invention, a substrate of Si (approximately $700\mu m$) comprising a layer of thermal SiO_2 on the surface (for example 200nm) is implanted initially with helium atoms under implantation conditions of $70keV-2x10^{16}He/cm^2$, and then implanted with hydrogen atoms under the conditions of $30keV-3x10^{16}H/cm^2$. The deepest profile is thus implanted first. This source substrate is then joined to a target substrate of fused silica (approximately $1000\mu m$) by direct bonding. A heat treatment around 300°C is then applied to the structure for a certain time (3 h, for example, or more if the weakening treatment is adapted.

Then, after bringing the structure back to ambient temperature, by means of a blade only scarcely inserted between the bonding interfaces and imparted with a movement pulse (i.e. a shock), self-supported splitting at the maximum of the hydrogen profile leads to the transfer of the Si thin film onto the fused silica substrate, without breakage or degradation of either of the substrates derived from the heterostructure after splitting (the fused silica substrate having the thin film of Si on the one hand, and the initial Si substrate having had the superficial thin film peeled from it on the other hand). The roughness of the surface transferred, measured at low frequency by profilometric method (of the order of 14 angstroms RMS at low frequency) and by atomic force microscopy (of the order of 75 angstroms at high frequency) of that transferred surface are substantially less than those which may be obtained in the case of H-implanted alone (32keV-$5.5x10^{16}H/cm^2$) annealed at 400°C for 2h using the progressive mechanical splitting method at ambient temperature (roughness at high frequency of the order of 90 angstroms RMS and roughness at low frequency of the order of 40 angstroms RMS).

Germanium on insulator

The above information may be generalized to the situation of a source substrate of solid germanium, with the following weakening parameters: dose 7×10^{16} H/cm^2 with an energy from 30 to 200 keV according to the thickness to be transferred, and annealing at 300°C for a certain time (typically from 30 min to 1 h, i.e. an operating window of 30 min).

After this heat treatment specific to these implantation conditions, the density of the microcracks present at the level of the implanted area is estimated

to be from 0.03 to 0.035 per square micron, their sizes are of the order of 7 to 8 square microns, and the area opened up by these defects as a percentage of the total area of the wafer is from 25 to 32%. The characteristics of the weakened area may appear similar to characteristics observed when the fracture is obtained thermally, but different from those obtained after a weakening treatment of 280°C - 15 min, which implies an assisted mechanical fracture, in which case, these values are lower: for example, the area opened up by the microcracks represents less than 10% of the total area of the wafer.

Silicon on insulator

In order to open the window of the process it may, for example, be preferred to implant a higher dose, for example at 30 keV - 1.10^{17} H/cm^2 and then to apply heat treatment at 350°C for 30 min. It is possible in this way to obtain a 1 to 2 min window for the appearance of the self-supported fracture phenomenon, nevertheless without leading to thermal fracture.

AsGa on insulator

The following conditions are applied:

- implantation 5×10^{16} at/cm^2; at 100 keV approx.,
- annealing at 250°C for from 3 to 30 minutes.

The self-supported fracture phenomenon may be observed when the weakening annealing is conducted in a window from 3 to 30 minutes.

References

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